If You Give the Sun a Telescope: Imaging Alien Earths as Seen by the Solar Gravitational Lens

Mason V. Tea, Wesleyan University

Advisor: Seth Redfield, Wesleyan University

Abstract

Contemporary methods of directly imaging exoplanets have yielded the first images of their kind, though none have yet allowed humanity to view the surface of an alien world. Resolving the fine structure of objects as small, dim and distant as exoplanets requires a telescope the proportions of which current technology is incapable of producing. One solution, a telescope concept dubbed the solar gravitational lens (SGL), utilizes the gravity of our own Sun as a means of focusing light from planets about other stars. While the SGL offers unparalleled angular resolution and magnifying power, the images it produces take the form of an Einstein ring about the Sun. Here we present `SunTracer`, a lensing simulation capable of fabricating the class of images the SGL will see. The ultimate goal of our research is to produce an algorithm for reconstructing source images of Earth-analogs from their Einstein rings; `SunTracer` is meant to provide a set of test images with known sources for this forthcoming algorithm.

Introduction

Exoplanets are extremely small, dim and distant objects, making imaging them directly a challenge. Characteristics of the host star, the planet itself and the telescope they are being observed with all constrain the types of planets that can be imaged this way. As a result, the catalogue of exoplanets directly imaged to date is quite small, each observed with low angular resolution, large orbital distance and radii on the order of 1-10 R_J (Marois et. al. 2019). These constraints have thus far prevented us from observing potentially habitable exo-Earths, which would possess a significantly tighter orbit and smaller radius than the exo-Jupiters observed to date.

With current technology, imaging this class of planets directly is, in fact, impossible. Achieving the angular resolution and light amplification necessary to resolve an exo-Earth at 30 pc, within a *single pixel*, would require a diffraction-limited telescope with a ~90 km aperture (Turyshev & Toth 2019). To achieve a 1000 square pixel image, an interferometer with a baseline of $12R_\oplus$ would be required (Turyshev et. al. 2019). Clearly, this is not realistic.

While a telescope with these proportions cannot be constructed, nature has provided us with a means of achieving the angular resolution and amplification power necessary to image Earth-analogs in exceptional detail: our own Sun. The solar gravitational lens, or SGL, consists of a modest 1-m class telescope placed at the Sun's gravitational focus and oriented towards the Sun. When the telescope, the Sun and a target exoplanet are perfectly aligned (*in syzygy*), an Einstein ring containing light from the planet is produced around the Sun's limb. Contained within this ring is an image of the planet's surface, with angular resolution on the order of 10^{-10} arcsec and amplification on the order of 10^{11} (Turyshev 2017).

The question of how the data contained within these Einstein rings are to be reconstructed is wide open, and this is where our research directs its attention. In preparation for an algorithm to do so, we have developed `SunTracer`, a general-relativistic raytracer which simulates syzygal lensing with known sources. It is meant to serve as a method of generating test images for this reconstruction algorithm.

Background

It is well known that light is deflected by the gravity of massive bodies and, as a result, deformed images of sources located behind such massive bodies can be seen as the light is bent around them and focused. Gravitational lenses are seen often in nature and have provided astronomers an invaluable tool for studying large-scale objects like galaxies, but these sources are far more often warped non-uniformly, caused in part by misalignment of source, lens and observer.

If, on the rare occasion, all three are in syzygy, what is produced is an Einstein ring, a relatively uniform distribution of source light in a ring observed about the outside of the lens. This is what the SGL seeks to take advantage of — collecting light focused gravitationally by the Sun from an exoplanet results in an Einstein ring containing an image of the planet's surface, possessing extreme angular resolution and magnification. Not only does the symmetry of the ring provide a less complex set of photon trajectories to consider, but this pristine alignment provides the maximum magnification possible (Turyshev & Toth 2018).

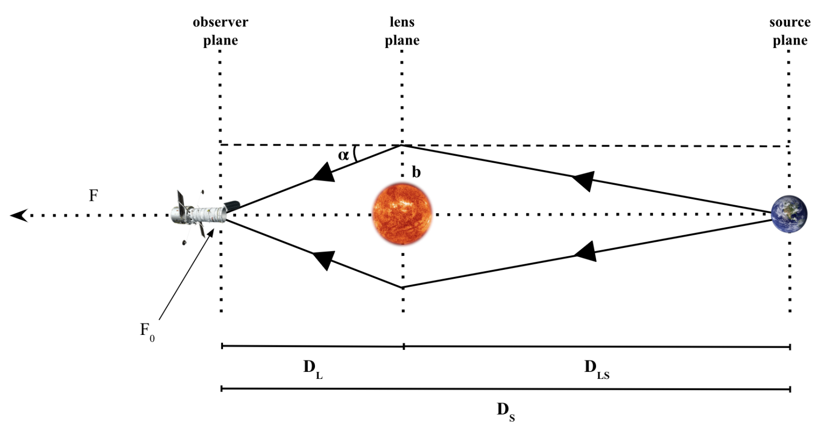

Fig. 1.— A diagram of the SGL. The minimum gravitational focus (F_0) of the Sun exists at ~550au and focusing continues along the focal axis (F) extending past this minimum. The angle at which light is deflected about the Sun, (α), is determined by its impact parameter (b), or its distance from the Sun's limb as it passes. Separations between the source, telescope and lens (D_L, D_{LS}, D_S), as well as b, affect the characteristics of the image.

Methods & Results

The culmination of this summer's research is `SunTracer`, a general-relativistic, raytracing gravitational lensing simulation, written with the parameters of the SGL in mind. `SunTracer` seeks to generate physically accurate representations of the images that will be taken by the SGL — Einstein rings, encoded with high-amplification, high-resolution data — so that deconvolution techniques have a set of SGL-class images with known sources with which reconstruction can be attempted.

`SunTracer` is a raytracer, adapted from Jorge Jiménez-Vicente's inverse ray-shooting code (Jiménez-Vicente 2016). What we want the code to yield fundamentally is a one-to-one photon map of the source image after being warped by the lens, and the method of raytracing lends itself naturally to this interpretation. From each pixel in the image, photons are sent out from the observer, through the lens plane and towards the source — those that hit the source plane are mapped on the observer plane, those that do not are excluded. This tracing technique for individual photons will aid in solving the inverse map mathematically, yielding the one-to-one forward map we are looking for.

In order to test the realism of our results, we simulated a 2-D Gaussian in the source plane, allowing us to see how the uneven brightness is distributed in the lensed map, shown in Figure 2. In this figure, the observer and the lens are slightly misaligned in order to demonstrate how different parts of the planet's surface will map to the Einstein ring. The pattern observed off-axis seems to agree with the SGL's PSF (Turyshev & Toth 2019).

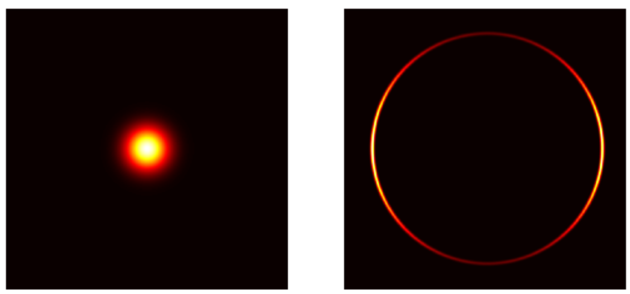

Fig. 2.— `SunTracer`'s lensed simulation (right) of a 2-D Gaussian source (left). The scale here (as well as in Figure 3) is exaggerated to show all the features of the ring; in practice, the width of the ring would span ~1 arsecond, depending on the SGL's configuration.

After verifying the simulation, we began work to implement real astronomical data into the simulation in place of false sources. Figure 3 shows RGB data from the Earth Polychromatic Imaging Camera (EPIC) camera aboard NASA's Deep Space Climate Observatory (DSCOVR) satellite lensed by `SunTracer`. The effect demonstrated by Figure 2 is less obvious here, if evident at all with the eyes alone, but images like these will allow preliminary reconstruction algorithms to investigate spatial structure in the simulated ring.

Future Work

Testing

In order to ensure that `SunTracer` is as close an approximation as our next steps require, we first hope to verify that the optical properties of the SGL are present in the simulation. These properties have been well-studied in the literature, providing us mathematical models to compare with (Turyshev & Toth 2018). Specifically, those we feel we can confirm are point-spreading, diffraction, gain and how these characteristics change with the orientation of the SGL.

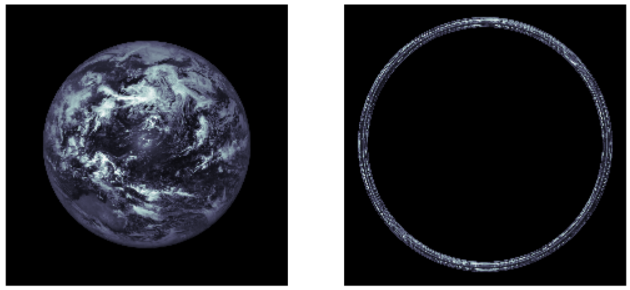

Fig. 3.— `SunTracer`'s lensed simulation (right) of an RGB source from NASA DSCOVR (left).

Deconvolution

Our ultimate goal is to invent a method of reconstructing source images from their Einstein rings. Producing `SunTracer` was an important step towards this goal — in order to verify that the inverse map from Einstein ring to source image is accurate, we first require a physically accurate forward map to work backwards from. With this tool now available to us, we can begin studying deconvolution techniques.

The purpose of the SGL is not to collect Einstein rings, but to extract the data contained within them. For this, we require a method of mapping the photons on the image plane (the Einstein ring) back into the source plane (the surface of the exoplanet). Unfortunately, the process is not as simple as reversing `SunTracer` and following the mapped photons back to the source — the optical properties' effect on the Einstein ring prevents this. We believe that the next step is to derive mathematically the inverse map and apply that transformation to the lensed images.

In addition to reconstructing images of individual points on the planet, a total reconstruction of the planet is necessary. The goal of the SGL is to produce 1000 square pixel images of the planets it observes, each Einstein ring representing only a single pixel containing a patch of the planet's surface. Figure 4 shows how each pixel maps itself onto its individual Einstein ring.

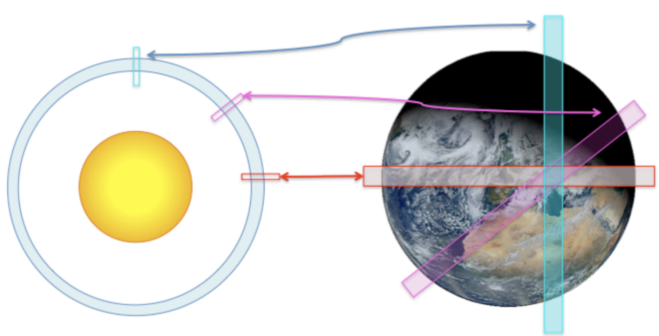

Fig. 4.— A figure from Landis (2016) which demonstrates how an individual pixel maps itself across the Einstein ring.

Spectroscopy

Our interest is specifically directed towards using the SGL to image habitable exoplanets. Seen in Figure 3, we have generated lensed images of the only habitable planet we have this data for so far.

However, the SGL will yield high-resolution spectroscopic data from the exoplanets' atmospheres in addition to optical images, and we hope to implement a means of extracting spectra from this data.

Dynamics

Of course, exoplanets are not static objects, and this is something that the SGL must account for. While mission design and pointing considerations due to orbital motion are left to the engineers, rotational and atmospheric motion will be important for reconstruction. In order to implement this into `SunTracer`, we must consider how we can use the discrepancies between Einstein rings to reconstruct a clean image of the planet's surface.

Conclusions

We believe `SunTracer` to be the logical first step in any subsequent course of action we choose to take. Not only does the simulation provide a dataset for reconstruction, but in ensuring that `SunTracer` matches theoretical predictions of the SGL's properties, we ourselves will be able to better understand the concepts and challenges involved.

Despite the conceptual novelty of the SGL, it is currently the only method proposed to achieve anywhere near the angular resolution it is capable of. Imaging the surface of an alien world would be an astonishing breakthrough and, with the SGL, observing those which are potentially habitable will likely make short work of finding life outside of the Solar system. For this reason more than any other, we believe that these methods are worth exploration.

Acknowledgements

Many thanks to my advisor, Seth Redfield, for his guidance this summer and over the two years I've worked with him, as well as his enthusiasm for the pursuit of this project despite its novelty to the both of us. Thanks also to the rest of the Wesleyan astronomy department for their support.

References

Jiménez-Vicente, J. in *Astrophysical Applications of Gravitational Lensing*, Mediavilla, E., Muñoz, J., Garzón, F., & Mahoney, T. (Eds.). (2016). Cambridge: Cambridge University Press.

Landis, G. A. 2016, arXiv e-prints, arXiv:1604.06351

Maccone, C., *Deep Space Flight and Communications: Exploiting the Sun as a Gravitational Lens*. (2009). Springer-Verlag Berlin Heidelberg.

Marois, C., Macintosh, B., Konopacky, Q., et al. 2011, American Astronomical Society Meeting Abstracts #217 217, 302.01

Turyshev, S. G., & Toth, V. T. 2019, arXiv e-prints, arXiv:1908.01948

Turyshev, S. G. et. al, B.A.A.S., Vol. 51, Issue 3, id. 23 (2019).

Turyshev, S. G. 2018, Journal of the British Interplanetary Society, 71, 361

Turyshev, S. G., & Toth, V. T. 2017, Phys. Rev. D, 96, 024008

Turyshev, S. G. 2017, Phys. Rev. D, 95, 084041

Turyshev, S. G., & Andersson, B.-G. 2003, MNRAS, 341, 577